

## P-23: Neutron Science and Technology

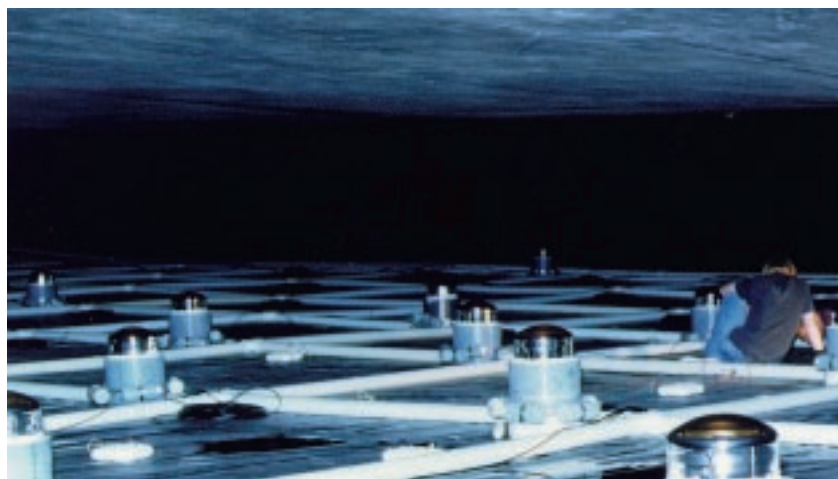
Mary Hockaday,  
Group Leader (1997)  
Geoffrey L. Greene,  
Group Leader  
(1995–1996)  
Susan Seestrom,  
Deputy Group Leader (1997)  
Frank H. Cverna,  
Deputy Group Leader  
(1995–1996)

### Introduction

Group P-23 (Neutron Science and Technology) applies its extensive experience in both particle detection and the recording of transient events to support the experimental program at the Los Alamos Neutron Science Center (LANSCE), to participate in a variety of Nuclear Weapons Technology (NWT) projects, and to carry out basic research in fundamental and applied physics. The work at LANSCE involves support of Laboratory programs in Science-Based Stockpile Stewardship (SBSS), Accelerator Production of Tritium (APT), and Energy Research (ER). The NWT projects in which P-23 participates include subcritical experiments; nonnuclear hydrodynamic experiments (AGEX-I) at either LANL or the Nevada Test Site (NTS); pulsed-power experiments for the High-Energy-Density Physics (HEDP) program; and archiving and analyzing data from past nuclear-weapons tests. The group's work in fundamental research focuses on nuclear and weak-interaction physics and on astrophysical phenomena involving the detection of solar neutrinos and ultrahigh-energy gamma rays. Applied research conducted by the group includes the development of quantum-information technologies, such as quantum computation and encryption (involving single-photon detection) and the application of imaging and neutron technologies to problems relevant to national defense or industry.

P-23 provides and improves imaging technologies including tomography and holography, wide-dynamic-range data acquisition and recording, and spectral measurements involving the detection of photons across 13 orders of magnitude in energy (infrared to ultrahigh-energy gamma rays) and neutrons across 15 orders of magnitude (ultracold neutrons to 800 MeV). The major experiments in which the group is involved are located at the following facilities: LANSCE, at both the Manuel Lujan Jr. Neutron Scattering Center (MLNSC) and the Weapons Neutron Research (WNR) facility; NTS; the Pegasus pulsed-power facility at Los Alamos; the Milagro site in the Jemez Mountains for detecting ultrahigh-energy photons from outside the solar system (Fig. I-5); off-site accelerators; and the Sudbury Neutrino Observatory (SNO) in Canada.

*Fig. I-5. Installation of the first set of photomultiplier tubes in the Milagro detector.*



## LANSCE Support

Data from previous weapons tests do not provide all of the data that we presently believe are required for the weapons laboratories to be able to assure the safety and reliability of the nuclear-weapons stockpile without nuclear testing. NTS experiments answered only a small part of the question of what happens to a weapon as its components age. The SBSS program is intended to put this and other assurance issues on a scientific basis without nuclear testing. Together with our colleagues in other groups, divisions, and laboratories such as Lawrence Livermore National Laboratory (LLNL), we are studying the following:

- the performance of chemical explosives, including changes as they age;
- the fundamental physics of plutonium, e.g., the phonon spectrum;
- the temperature of materials undergoing hydrodynamic instabilities; and
- nuclear cross sections that are required for better analysis of radiochemical data from previous weapons tests.

For these studies we use neutrons from LANSCE, including moderated neutrons from the MLNSC, moderated neutrons with tailored time-structure from the WNR “Blue Room,” and unmoderated neutrons from the WNR fast-neutron source. Neutron spectroscopy by time-of-flight techniques is central to all of these projects.

In support of the SBSS program, research in nuclear physics is carried out at the WNR facility with neutrons from below 1 MeV to 800 MeV. A large array of Compton-suppressed germanium detectors (the GEANIE detector) has recently been installed to measure, with very high resolution, gamma rays from neutron-induced reactions. This is a joint project between LLNL and P-23, with additional participation by universities and other LANL groups. Nuclear structure and nuclear reactions can be studied with this new capability, which is described in detail in a Research Highlight of this Progress Report. Our interests at present are in the  $^{239}\text{Pu}(n,2n)^{238}\text{Pu}$  cross section, where different nuclear-reaction models give markedly different predictions, and in the nuclear structure area of “complete spectroscopy,” where models of nuclear-structure symmetries and the transition from order to chaos in nuclear spectroscopy can be tested.

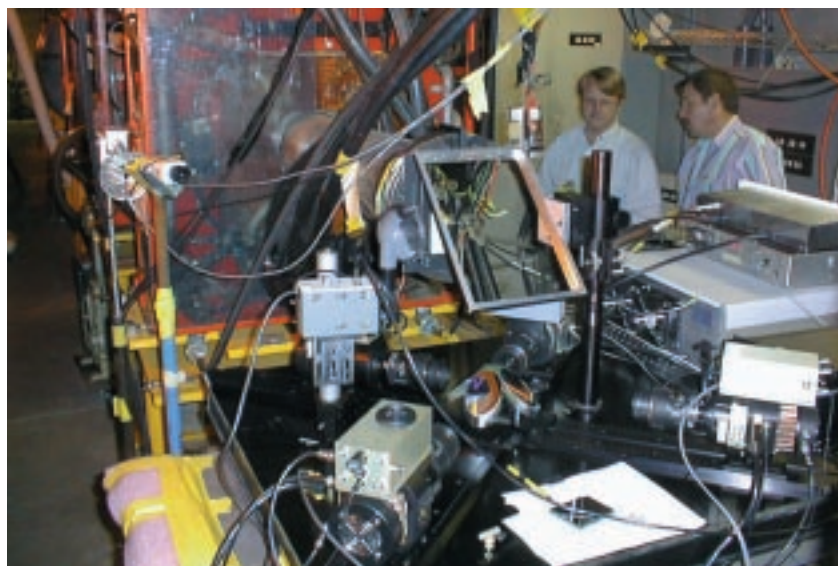
An important element of the SBSS program at LANSCE is hadron radiography. P-23 is supporting this effort with a cold-neutron radiography project at the MLNSC, by participation with P-25 and LLNL in the 800-MeV proton-radiography project at LANSCE, and in the high-energy neutron-radiography project at WNR. P-23 developed a cooled, charge-coupled device (CCD)

imaging system with fast gating and image intensification for use in hadron radiography (Fig. I-6). The system was first applied to radiograph a low-density material encapsulated in a high-density casing, using neutrons produced at the WNR in the 5- to 200-MeV energy range. The group has also collaborated with P-25 in the development of a pixelated, gas-amplification wire-chamber detector for hadron radiography.

As part of the SBSS program, P-23 has operated the WNR neutron sources and provided experimental support to experiments on the 6 beamlines at the WNR fast-neutron spallation source, WNR "Blue Room" experiments where the 800-MeV proton beam can be accessed directly, and 5 beamlines at the MLNSC. In the future, the operation of these facilities will be under the control of LANSCE Division, but we anticipate that technical experimental support will continue to be supplied by P-23.

The goal of the APT program is to explore the possibility of using accelerator-driven transmutation of helium to supply the U.S. nuclear-weapons stockpile with tritium. Production of tritium from traditional reactor sources was terminated in the late 1980s. Because tritium decays with a 12-year half-life, a continuing supply of tritium is necessary to maintain the stockpile at any given level. P-23 supplies basic nuclear-physics data, performs integral tests of the calculated neutronic performance of benchmark systems, develops beam diagnostics, and participates in irradiation studies of components for this program. Basic nuclear-physics data include neutron total and reaction cross sections and activation data, mostly measured with the spallation neutron source at WNR. Integral tests employ small-scale mockups of the accelerator target and of the neutron-reflecting blanket. These allow the initial neutron production, the final tritium production, and intermediate steps to be quantified and compared with calculation. Beam diagnostics utilize P-23's imaging capabilities. An important milestone was reached with the demonstration that the superconducting cavity continues to perform well even when irradiated directly with the

*Fig. I-6. Shown in the lower half of this photograph are the four CCD cameras that P-23 operates as part of the dynamic proton-radiography project.*



LANSCE proton beam. These data-measurement activities and integral demonstrations are continuing as the APT program progresses.

We work with LLNL and Ohio University at WNR on the measurement of neutron total cross sections. This quantity describes the probability of neutron interactions with materials and is therefore central to all calculations of neutron transport in macroscopic systems, such as targets and shielding in the APT project, nuclear weapons, proton- and neutron-therapy facilities, and basic nuclear-physics accelerator experiments. The WNR facility is ideal for these measurements because of its excellent neutron-source characteristics: a subnanosecond pulse width, low gamma-flash, and high repetition rate. Accuracies on the order of 1% are routine with this approach over a neutron energy range of 5–600 MeV. The data rate is high; the average run time necessary to achieve this accuracy for a given material is about 1 day.

Support of ER programs at LANSCE is described in the later section on Basic Research.

### **NWT Support**

With the end of nuclear testing, our knowledge of the ways in which actual weapons work relies on the data that were obtained from tests at NTS and test locations in the Pacific Ocean. Saving, analysis, and documentation of NTS weapons test data is a major responsibility of P-23 and the other groups responsible for these measurements and is crucial to the success of SBSS. Fortunately, physicists and engineers who performed the original measurements are still available to analyze their data and correlate the data of different events. In addition, new scientists are being trained in the technologies of making such measurements in case the need should arise for future underground tests. P-23 concentrates on the analysis of pinhole neutron experiments (PINEX) imaging data and on neutron emission measurements (NUEX and THREX). These data complement reaction history and radiochemical measurements, which are made by other groups. The process of saving, reanalyzing, and documenting these data has allowed us to obtain a better understanding of the underlying physical processes that generated them. Comparison of the results from different tests is allowing us to study systematically the behavior of nuclear explosives.

If SBSS is to be successful in allowing us to certify the performance of our nuclear weapons in the absence of nuclear testing, we must develop better physics models and incorporate them into computer codes that calculate explosive performance. We must be able to validate these codes against the NTS data that we have. Only then will we be able to address with confidence the issues of aging and remanufacture of our stockpile weapons.

P-23 is participating in a series of experiments to explore weapons-physics issues of a more microscopic nature than those explored in the underground NTS tests of nuclear explosives. We use chemical explosives and pulsed-power machines such as Pegasus as drivers to examine issues such as the equation of state (EOS) of shocked materials, formation and transport of ejecta from shocked surfaces, and growth of hydrodynamic instabilities. Underground experiments (UGEX) that involve plutonium are planned for the U1a facility at NTS. Experimental tools, such as gated visible imaging, gated x-ray imaging, holography, and infrared (IR) temperature measurements, are used to study the physical phenomena. We are developing fast IR imaging. The data that we can thus obtain are used both to understand the physical processes and, as computer models are developed, to benchmark the calculations. These experiments will greatly improve our understanding of nuclear-weapons physics.

A critical—and currently limiting—component to a number of Laboratory weapons-program experiments is an imaging sensor that can be gated (or shuttered) in the few-nanosecond to subnanosecond regime, can achieve a high frame (or data) transfer rate (up to  $10^7$  frames per second), has a high quantum efficiency (1% to 50%) and sensitivity (<10 photons per pixel detection), and covers the spectrum from visible light into the near IR (380 nm to 5  $\mu$ m in wavelength). Such advanced-technology imaging capability is not available commercially, and the technology for achieving such imaging is presently state of the art or in development. Prior to the cessation of testing, advanced imaging was required for underground shots at NTS, and the Laboratory (previously in J-12 and P-15, and then in P-23) had developed an in-house capability to meet the needs of the weapons program. After suspension of the underground testing program, the Laboratory's SBSS program is forging above-ground experiments (AGEX) that are again placing ever increasing demands on the imaging and technology development capabilities of the weapons laboratories. Some of the areas in which advanced technology imaging systems are required are the following:

- AGEX;
- subcritical UGEX at NTS;
- hadron radiography;
- shock break-out experiments;
- Advanced Hydrotest Facility diagnostics;
- LANSCE beam diagnostics;
- Trident, Pegasus, HEDP-program, and Atlas diagnostics; and
- plasma physics.

## Basic Research

Excitations of complex nuclei are characterized by resolved, well-spaced levels at low excitation. As the excitation energy increases, the number of levels increases until the levels overlap and cannot, in principle, be resolved. The level density in this unresolved region may have underlying structure related to the levels that exist at low excitation. At very high excitation, it is generally believed that the nucleus behaves like a gas of neutrons and protons, a so-called Fermi gas. The transition from the ordered states at low excitation to the disordered Fermi gas is of great interest, both for the basic physics of phase transitions in nuclear matter and for modeling the nuclear reactions of astrophysics and nuclear explosives, where short-lived nuclides can contribute significantly to nucleosynthesis and to the dynamics of a reacting system. At WNR we are studying nuclear level densities through neutron-induced  $(n,z)$  reactions that produce charged particles, such as reactions where protons or alpha particles are produced. By studying the evaporation spectra, we can deduce the level density in excited nuclei. Furthermore, we have two other techniques for studying level densities, both of which rely on the intense neutron source at WNR and the fact that the  $(n,z)$  reactions can be studied as a function of neutron energy over a wide energy range.

Because of enhancements engendered by the relatively long lifetimes of their states, compound nuclei provide an excellent laboratory for studying violation of basic symmetries. We have observed parity violation in neutron resonance reactions for a large number of resonances in more than a dozen target isotopes. With techniques developed by P-23 and our partners, we are able to identify very weak p-wave resonances in which parity violation can occur and be observed with amplitudes of up to 10% of parity-conserving interactions. Nuclear theory predicted that the sign of the parity-violating effect should be random, and for all but one nucleus, it appears to be. The exception is  $^{232}\text{Th}$ , where the violation for the eight resonances with the strongest effects are all of the same sign, which would have a less than 0.25% probability of occurring if the sign were indeed random. We have investigated all of the readily available isotopes at maxima in the p-wave strength function and therefore are bringing this research to a close. The case of  $^{232}\text{Th}$  remains an enigma.

We are also active in other tests of fundamental symmetries in the beta decay of trapped atoms and of free neutrons. Sensitive tests of the parity-violating beta-spin asymmetry correlation in the decay of  $^{82}\text{Rb}$  constitute one experimental sequence that we anticipate will yield results with a precision one order of magnitude greater than any previous experiment. In studies of the decay of the free neutron, we initiated the EMIT ("time" reversed) collaboration to pursue a search for time-reversal invariance violation (TRIV). For this we have designed an experiment that promises to be seven times more sensitive than previous experiments.

As a follow-on to these measurements, we are planning to study parity violation in the reaction  $n + p \rightarrow d + \gamma$ . We have demonstrated the feasibility of many aspects of this experiment. We demonstrated that it was possible to achieve the counting statistics limit when taking a current signal from a vacuum photo diode that viewed a CsI gamma detector at the projected rates of a parity-violation experiment. The magnetic-field sensitivity of the current signal was shown to be small— $2 \times 10^5 \text{ G}^{-1}$ . The spectral densities of position and intensity drifts in the LANSCE beam were also very small.

Finally, we measured the total cross section of the neutrons of  $^3\text{He}$  with an accuracy of  $10^{-3}$  in the energy range 0.5–500 eV. This cross section is important in understanding the performance of the polarized  $^3\text{He}$  spin filter that will be required for such an  $n + p \rightarrow d + \gamma$  experiment and for studies of the beta decay of polarized neutrons.

The dispersion relation between parity violation in spin rotation and transmission has been investigated by our study of the parity-violating rotation of the plane of neutron polarization when a transversely polarized neutron beam passes through a sample of  $^{139}\text{La}$ . Lanthanum-139 has a resonance at 0.734 eV that exhibits large parity violation in transmission. This experiment also serves as a prototype for future experiments to study time-reversal symmetry violation in neutron transmission.

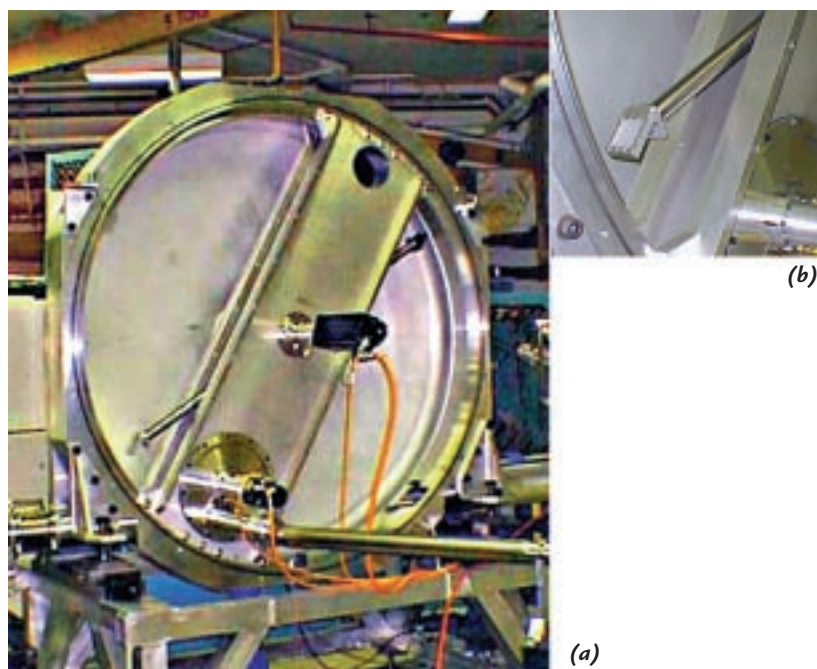
The basic neutron-proton interaction is studied at WNR in two types of experiments: simple  $n$ - $p$  scattering and the more complicated situation where a gamma ray is emitted when the two particles interact, called neutron-proton bremsstrahlung (NPB). Simple (elastic)  $n$ - $p$  scattering at certain angles and energies is sensitive to the interaction mediated by the exchange of a single  $\pi$ -meson, which is the most basic of interactions in meson-exchange theory. Despite decades of work on this interaction, there still is significant disagreement on the fundamental pion-nucleon coupling, and we are working to resolve this disagreement, which has widespread ramifications in the binding of nuclei and in astrophysics. Basic interaction models also give different predictions for NPB, which has not been studied before with differential measurements. The measurements are now being made by a group from the Massachusetts Institute of Technology together with P-23.

Ultracold neutrons (UCNs) were first produced at LANSCE in 1996 by the use of a rotor reflector. These neutrons travel with speeds of less than 8 m per second. We are continuing to develop this source with improved cold moderators and better rotor

reflectors (Fig. I-7). We plan to use this source in the investigation of the radioactive decay of free neutrons and, possibly, in the search for an electric dipole moment (EDM) of the neutron. Both of these projects aim at detecting physics beyond the standard model of strong and electroweak interactions. P-23 is participating with P-25 and others in the design of an EDM experiment at the proposed long-pulse spallation source (LPSS) at LANSCE that will use UCNs produced by the inelastic scattering of cold neutrons in superfluid helium.

Very-high-energy gamma rays from the cosmos have been detected when they enter the atmosphere and produce an air shower of particles. The Milagro project, located in the Jemez Mountains above Los Alamos and inaugurated in 1995, is the construction and operation of a high-efficiency observatory for gamma rays in the energy range around  $10^{14}$  eV. This observatory involves a joint project of Los Alamos and a large number of universities. It will be especially well suited for the study of episodic or transient gamma-ray sources, that is, for recording gamma-ray bursts. It is operational 24 hours a day, 365 days a year, and its field of view is nearly half of the sky. Milagro began providing operational data in 1996 and soon will be fully instrumented.

The number and spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. For many years we have worked with scientists from the Soviet Union and, now, the Former Soviet Union to detect neutrinos by using large quantities of gallium far underground in the Caucasus Mountains. This is the SAGE (Soviet-American Gallium Experiment) collaboration. The result from this lengthy study was that the number of neutrinos detected is about half of that predicted by the best solar and neutrino models. Now we are



*Fig. I-7. (a) UCN rotor with (b) a close-up of the mica crystal package.*

collaborating in the development of a neutrino observatory more than a mile underground in Sudbury, Ontario. The SNO (Sudbury Neutrino Observatory) detector will soon be operational and consists of an acrylic vessel holding 1,000 tonnes of heavy water surrounded by another vessel with 8,000 tonnes of light (regular) water. All three flavors of neutrinos (electron, muon, and tau) will be detected. Development of this detector includes the design and fabrication of very-low-background  $^3\text{He}$  detectors and new electronics. As a spin-off, the very sensitive, low-background detectors developed for the observatory will be used to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by “flipping” bit patterns.

### **Applications of Basic Research**

Quantum computation, a field in its infancy, promises a new approach to solving some problems (regarded as intractable in classical computation) by using the quantum-mechanical superposition of many states (numbers) at once. To realize such a computer, we are developing a system with cold, trapped atoms that represent the quantum-mechanical states. Quantum logical operations are performed with laser manipulations of the states of the trapped atoms. Using conventional lasers, we have recently succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits. We are developing advanced diode lasers to perform the same operation, but with much reduced power requirements and cost.

Quantum mechanics provides an approach to unbreakable cryptographic codes that not only can transmit the code “key” with security but that can also reveal the presence of eavesdropping. We have demonstrated this quantum cryptography over 48 km of fiber-optic cable and are developing longer transmission demonstrations. In a related effort, we have demonstrated transmission of a “key” through more than 200 m of air and through this technology are aiming at establishing secure communications between ground-based stations and low-earth-orbit satellites.

Using the complementary wave- and particle-like nature of light, it is possible to determine the presence of an object without any photons being absorbed or scattered by it. We are carrying out fundamental studies in such “interaction-free measurements” and have begun investigating the practical implementation of “interaction-free imaging,” where these measurement techniques are used to take a (pixelated) image of an object, again with the goal of negligible absorption or scattering; at present, a resolution of better than  $10\text{ }\mu\text{m}$  has been achieved, and we hope to improve this even further.

We support Department of Defense (DoD) programs in mine detection and seeker applications. For the detection of land mines, we are investigating the use of neutrons as an interrogating probe, with the detection of the resulting activation gamma rays as the positive signature. High-intensity neutron sources are necessary for the required sensitivity, and we are developing them in collaboration with other groups. Accelerator sources are strongly preferred because their energy can be tuned and specified, and they can be turned off when not in use. We are assessing the required sensitivity of detection, using our extensive experience acquired in developing neutron detectors for the Nuclear Test Program and for accelerator-based experiments. P-23 has also developed a laser-based, range-gated imaging system for the airborne detection of submerged mines. The system has undergone testing in both controlled-tank and open-sea environments. We have supported seeker (target identification) programs with range-gated laser distancing and ranging (LADAR) experiments carried out at the Wright Laboratory's laser range at Eglin Air Force Base. These experiments are part of a joint DOE/DoD technology-development program.

The further development of spallation neutron sources for basic physics research and for applications will depend on the availability of reliable targets that can withstand very high heat loads from accelerator beams. Together with researchers at the Institute for Physics and Power Engineering in Obninsk, Russia, we are developing a molten-metal target that promises to handle much higher heat loads than solid targets. Our Russian coworkers have had extensive experience in using molten-metal cooling in fission reactors. Using the intense, 800-kW LANSCE proton beam, our goal is to test their design of such a target. We are developing a small molten-metal test loop as a first step before the large Russian components are subjected to the full-intensity beam.

We are studying the feasibility of including a cryogenic source of UCNs in the design of the proposed LPSS. Preliminary indications are that if a frozen deuterium source could be operated at 5 K in a flux of neutrons at LPSS densities with a Maxwellian temperature of less than 80 K, it would produce usable UCN densities at least 400 times greater than those presently available anywhere in the world. Such a world-class source of UCNs at LANSCE would open up new opportunities for experiments in fundamental physics and the possibility of novel applications to materials science. P-23 will continue to provide guidance for this project throughout the preliminary and engineering phases of the LPSS design.